EUROPEAN SOUTHERN OBSERVATORY

Organisation Européenne pour des Recherches Astronomiques dans l'Hémisphère Austral
Europäische Organisation für astronomische Forschung in der südlichen Hemisphäre

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APPLICATION FOR OBSERVING TIME PERIOD: **70A**

To be submitted only to: proposal@eso.org
Important Notice:

By submitting this proposal, the PI takes full responsibility for the content of the proposal, in particular with regard to the names of COIs and the agreement to act according to the ESO policy and regulations, should observing time be granted

1. Title Panel: **A–5**
MATURE STELLAR POPULATIONS IN A GALAXY PROTOCLUSTER AT REDSHIFT TWO

2. Abstract
The z=2.16 radio galaxy PKS 1138−262 resides in a protocluster, traced by numerous confirmed Lyα and Hα emitters and an overdensity of galaxies with $I-K>5$. This system affords us the opportunity to study cluster galaxies close to the mean star formation redshift of early-type systems. A flat Λ=0.7 universe is $\sim$3 Gyr old at z=2.16, so galaxies in this protocluster could have substantial mature stellar populations which formed at z>2, populations not detectable by emission-line searches. We propose to study the ages and masses of these mature stellar populations in this z=2.16 protocluster. We will identify the redshifted 4000 Å+Balmer break by combining existing BIK imaging with deep new $z'JH$ imaging (which also provides sensitivity to reddened star-forming galaxies). Moreover, VLT image quality will enable the study of the color and dispersion of the red sequence of morphologically selected early-type cluster galaxies at higher redshift than in any previous work.

3.

Run	Telescope	Instrument	Time	Month	Moon	Seeing	Sky Trans.	Obs.Mode
A	UT4	FORS2	1h	mar	g	$\leq 1.0''$	CLR	s
B	UT1	ISAAC	7h	mar	n	$\leq 0.6''$	CLR	s
C	UT1	ISAAC	4h	mar	n	$\leq 0.8''$	CLR	s

4. Number of nights/hours Telescope(s) Amount of time
a) already awarded to this project:
b) still required to complete this project:

5. Special remarks

6. Principal Investigator: P. HALL (P. Universidad Catolica, RCH, phall@astro.puc.cl)
CoI(s): L. PENTERICCI (MPIA-Heidelberg, D), G. MILEY (Sterrewacht Leiden, NL), F. BARRIENTOS (P. Universidad Catolica, RCH), J. KURK (Sterrewacht Leiden, NL)

7. Is this proposal linked to the PhD thesis preparation of one of the applicants?

8. Description of the proposed programme

A) Scientific Rationale:

Galaxy clusters provide invaluable laboratories for the study of the formation and evolution of galaxies and large-scale structure. Clusters are observed to have a large population of bulge-dominated or 'early-type' galaxies (the morphology-density relation; Dressler 1980). Cluster early-type galaxies have predominantly old, red, quiescent stellar populations both at low redshift and out to z=1.3, the current limit of cluster galaxy studies (Schade et al. 1997, Rosati et al. 1999). Studies of this 'red sequence' of early-type galaxies to z=1.3 have shown that ~50% of the stars in such galaxies must have formed at $z\geq 2$ (van Dokkum & Franx 2001). Star-forming galaxies are of course common at z>2 (Steidel et al. 1996). In addition, some optically faint galaxies with red $J-K$ colors indicative of dominantly old (or possibly dusty) populations at $z\gtrsim 2$ *have* been identified — even if they are uncommon (Fontana et al. 2000) — in deep small-area searches (Stiavelli et al. 1999, Dickinson et al. 2000, Totani et al. 2001) and along AGN sightlines (Francis et al. 1997, Hall et al. 2001). Furthermore, there are a handful of spectroscopically old galaxies at z=1.5 (Spinrad et al. 1997, Stockton 2001) in which star formation was largely finished by $3\lesssim z\lesssim 5$ (Nolan et al 2002, Bruzual 2002; cf. Le Borgne & Rocca-Volmerange 2002).

Thus, a considerable amount of star formation in the universe occurred at z>2 (Peebles 2002), especially in clusters. In agreement with this, despite the multiwavelength Butcher-Oemler effect of an increasing fraction of star-forming galaxies in clusters out to $z\sim 1$ (Rakos & Schombert 1995, Smail et al. 1999, Duc et al. 2002, Best 2002), and despite 'progenitor biases' (van Dokkum & Franx 2001) such as the apparent widespread morphological transformation of spirals into S0s at $z\lesssim 0.55$ (Dressler et al. 1997), clusters have not yet been directly observed which completely lack a well-defined red sequence because *all* of their early-type galaxies are still forming, or recently stopped forming, the bulk of their stars. The red sequence must have been largely in place at z>1.3, and probably z>2, and thus studies of early-type cluster galaxies must extend to these redshifts.

B) Immediate Objective:

The z=2.16 radio galaxy PKS 1138−262 resides in a protocluster of galaxies. There are numerous spectroscopically confirmed Lyα and Hα emitting galaxies in the field, which trace the current star formation in this protocluster. Also, one confirmed and three candidate Lyα emitters have $I-K\gtrsim 3.5$, similar to the handful of known high-z galaxies which show both ongoing star formation and substantial mature, red stellar populations (Francis et al. 1997; cf. Stiavelli et al. 2001). Considering even redder galaxies, the density of objects with $I-K_s>5$ in this field (Fig. 1) is more than twice that predicted by blank field surveys: we have 14 objects to K_s=21, where only 6±2 are expected (Scodeggio & Silva 2000). The extremely red objects are likely to be at the AGN redshift, as in other AGN fields (Hall & Green 1998, Cimatti et al. 2000). (Note that the confirmed emitters have a bimodal velocity distribution, with two peaks separated by ~1800 km s^{-1}. However, even if this protocluster is two separate structures, for studies of old stellar populations in overdense regions at high redshift the large-scale velocity field of the galaxies is not likely to be of great importance.)

Structure formation models tell us that star formation begins earliest in the most overdense regions. Since much star formation appears to have occurred at z>2, and since a flat Λ=0.7 universe is ~3 Gyr old at z=2.16, we expect a range of ages in the stellar populations of galaxies in this protocluster at z=2.16. **Thus we now propose to study the mature stellar populations in this protocluster** via rest-frame optical selection of galaxies and photometric identification of the Balmer and 4000 Å breaks. The Balmer break at ~3648 Å strengthens with age for stellar populations 0.05–1 Gyr old (see Shapley et al. 2001), while the 4000 Å break strengthens with age for $\gtrsim$1 Gyr old populations, as well as with metallicity (Hamilton 1985). With *BIz'JHK*$_s$ photometry, spanning 0.13-0.73μm at z=2.16, we will compute photometric redshifts accurate to $|\Delta z/(1+z)|\sim 0.1$, sufficient to identify probable cluster members to K_s=21.25 (K_{AB}=23.15). These estimates are scaled from the results of Rudnick et al. (2001); for early-type galaxies, the accuracy should be higher ($|\Delta z|<0.1$; Kodama et al. 1999). The photometric redshifts and SEDs will enable us to model the stellar populations in these galaxies (parametrized, e.g., by age, $E(B-V)$, and star formation timescale τ) to estimate their current star formation rates and the stellar masses in their young and old populations (Franceschini et al. 1998, Brinchmann & Ellis 2000, Papovich et al. 2002).

At $z\geq 3$, Shapley et al. (2001) have shown that Lyman-break dropouts are not exclusively young, though 80% do have best-fit ages $\lesssim$1 Gyr. Also, Rudnick et al. (2001) find numerous $z\sim 3$ galaxies in the HDF-South which are quite luminous in rest frame V. Such galaxies must have considerable mass in mature stellar populations, which bodes well for detection of such populations in galaxies in this protocluster at z=2.16.

Moreover, with seeing ≤0.6" in H and K_s, it will be possible to isolate bulge-dominated galaxies – the morphological red sequence – and study their colors and the scatter in their colors at z=2.16, as well as the Kormendy relation between central surface brightness and effective radius (Fig. 2). When compared to local samples, the Kormendy relation and the absolute color of the red sequence yield the amounts of luminosity and color evolution undergone by early-type galaxies between now and z=2.16. (The Kormendy relation also affected by size evolution in mergers.) The scatter in colors of galaxies on the red sequence arises predominantly from the scatter in their ages. The color scatter should increase near the epoch where the scatter in ages is comparable to the mean age. This assumes a morphologically defined red sequence exists at such redshifts, which might not be the case due to the effects of 'progenitor bias' – the removal of morphologically peculiar (e.g. interacting,

8. Description of the proposed programme (continued)

merging, and/or dusty star-forming) early-type galaxy progenitors from a morphologically defined sample (van Dokkum & Franx 2001). If the majority of the stellar populations in early-type galaxy predate the assembly of the galaxies in which we see them at $z \lesssim 1$, at high redshift there could be a well-defined red sequence in color but not in morphology, if no significant fraction of morphological early-type galaxies has assembled sufficiently to show relaxed morphologies by that redshift. van Dokkum et al. (1999, 2000) used HST images to show that in a cluster at z=0.83, the morphological red sequence has a small color scatter but that a population of morphologically peculiar mergers exists with similarly red colors but a larger scatter. These objects were more common in the outskirts of the cluster, which may hold for other $z\sim1$ clusters: a large population of non-bulge-dominated objects with the colors of the red sequence does not seem to be present in the core of an X-ray selected cluster at z=1.27 (with one spectacular exception; van Dokkum et al. 2001) nor an optically-selected cluster at z=0.97 (Fig. 2a; Barrientos et al. 2001). However, this may just mean that the era of morphological transformation of ellipticals in the cores of rich $z\sim1$ clusters lies at even higher z. In our protocluster at z=2.16, we may find a red sequence which is only well-defined in the color-magnitude diagram, or one which is also populated predominantly by recognizably bulge-dominated galaxies, or neither of the above. But whichever case is correct, the morphological distribution of the red galaxies and the color distribution of the bulge-dominated galaxies in our fields will constrain the evolution of early-type cluster galaxies at a higher redshift than previous studies.

REFERENCES: Barrientos et al. ApJL submitted / Best 2002 MNRAS in press (a-ph/0203318) / Brinchmann & Ellis 2000 ApJL 536 L77 / Bruzual 2002, Rev. Mex. Fisica in press (a-ph/0202178) / Cimatti et al. 2000 MNRAS 318 453 / Connolly et al. 1995 AJ 110 2655 / Dickinson et al. 2000 ApJ 531 624 / Dressler 1980 ApJ 236 351 / Dressler et al. 1997 ApJ 490 577 / Duc et al. 2002 A&A 382 60 / Fontana et al. 2000 AJ 120 2206 / Franceschini et al. 1998 ApJ 506 600 / Francis et al. 1997 ApJL 428 L25 / Hall et al. 2001 AJ 121 1840 / Hamilton 1985, ApJ 297 371 / Kodama et al. 1999 MNRAS 302 152 / Le Borgne & Rocca-Volmerange 2002, A&A in press (a-ph/0202359) / Liu & Green 1998 AJ 116 1074 / Nolan et al. 2002 MNRAS in press (a-ph/0103450) / Papovich et al. 2002, a-ph/0201221 / Peebles 2002 a-ph/0201015 / Pentericci et al. 2001 ApJS 135 63 / Rakos & Schombert 1995 ApJ 439 47 / Rosati et al. 1999 AJ 118 76 / Schade et al. 1997 ApJL 477 L17 / Scodeggio & Silva 2000 A&A 359 953 / Smail et al. 1999 ApJ 525 609 / Rudnick et al. 2001 AJ 122 2205 / Shapley et al. 2001 ApJ 562 95 / Spinrad et al. 1997 ApJ 484 581 / Steidel et al. 1996 ApJ 462 17 / Stiavelli et al. 1999 A&A 343 25 / Stockton 2001 ASP Conf. Ser. 245 p. 517 / Totani et al. 2001 ApJL 558 L87 / van Dokkum et al. 1999 ApJL 520 L95 / van Dokkum et al. 2000 ApJ 541 95 / van Dokkum et al. 2001 ApJL 552 L101 / van Dokkum & Franx 2001 ApJ 553 90 / Waddington 1998 a-ph/9801149.

C) Telescope Justification: This study of the most distant candidate early-type cluster galaxies to date requires the largest telescopes to date, as well as the proven excellent image quality of VLT in the near-IR. The equivalent NTT request would be ~6.5 nights, *4 of them with consistent <0.6" seeing.* ISAAC data in hand shows that robust morphological galaxy classification is possible at z=0.97 with such seeing (Fig. 2). Since the angular diameter distance in a Λ=0.7 flat universe is roughly constant from z=1 to z=2.16, such seeing will also suffice at z=2.16, as long as we image deep enough in the rest-frame optical (by coadding H and K_s).

For accurate photometric redshifts and SED constraints at z=2.16, the most important filters are z', J and K_s, sampling the rest-frame region around the 4000 Å break, which falls in the middle of the J band at $z = 2.16$. In particular, z' band samples close to rest-frame U, which will enable direct comparison with local and low-redshift galaxy clusters; U is the bandpass most sensitive to star formation which has been studied in large numbers of clusters. H-band imaging is also important, however, since $J-H$ is essentially a linear function of redshift for mature populations at $2<z<2.5$ (Waddington 1998). H data thus enables excellent redshift sensitivity for separating cluster galaxies from foreground and background objects, and as a second filter (besides K_s) above the 4000 Å break, it also improves the separation of dust-reddened galaxies from galaxies dominated by mature stellar populations. (For example, the colors of the $I-K_s>5$ objects in this field could arise in dusty starbursts rather than mature stellar populations, but z'- and H-band data will break this degeneracy: early-type galaxies should be red in $z'-H$ but relatively blue in $I-z'$ and $H-K$, whereas dusty star-forming galaxies should be red in all three colors. On the other hand, moderately star-forming galaxies at the cluster redshift should be generally blue, but with a red $z'-H$ caused by the Balmer+4000Å breaks.) With deep $z'JHK_s$ data we will be able to compute accurate photometric redshifts at z=2.16, something we have *not* been able to do with existing IK_s and shallow JH data. This is not surprising; many studies have shown that for accurate photometric redshifts and galaxy SED typing, there is simply no substitute for deep data below, around, and above the redshifted 4000Å break (Connolly et al. 1995, Liu & Green 1998, Kodama et al. 1999). Lastly, coupled with z' data, existing BI data will enable identification of $z \lesssim 1$ galaxies, reducing contamination in the cluster sample, and will yield rest-frame far-UV star formation rates for photometric-redshift identified cluster galaxies for comparison to those of Lyman break galaxies at $z>2.5$ (Steidel et al. 1996).

D) Observing Mode Justification (visitor or service): Service mode is best for this project: we require only 1 hr with FORS2, and $<0.6''$ seeing for most of our IR imaging, which cannot be guaranteed in visitor mode.

E) Strategy for Data Reduction and Analysis: Our entire team is experienced with optical and near-IR image reduction and analysis. Barrientos has extensive experience with quantitative galaxy morphology.

8. Attachments (Figures)

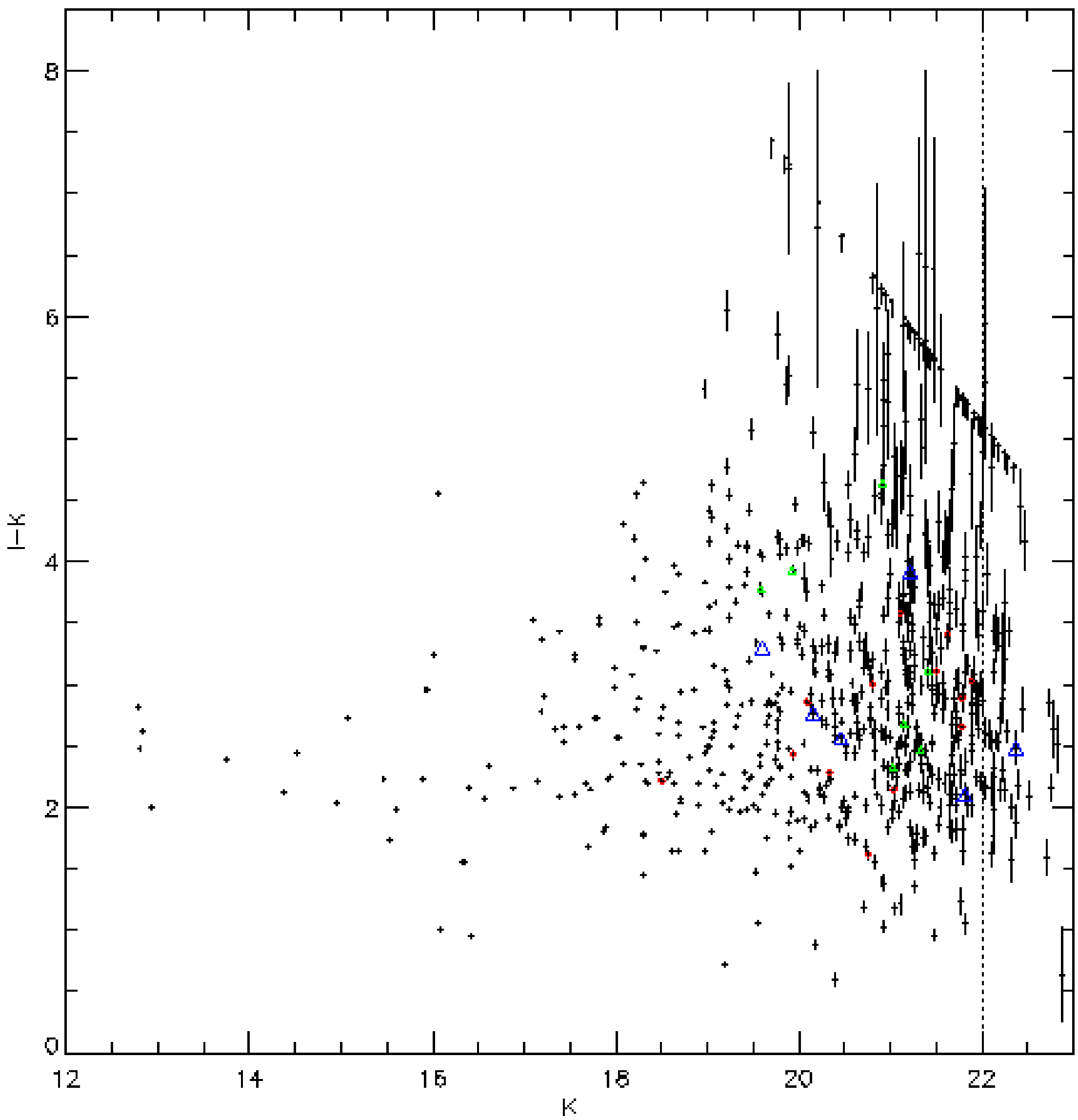

Fig. 1: $I - K_s$ vs. K_s color distribution in the ISAAC fields around 1138−262. The density of objects with $I - K_s > 5$ is more than twice that predicted by blank field surveys: we have 14 objects to K_s=21, while one would expect 6±2 (Scodeggio & Silva 2000). This suggests an association of these extremely red objects with the z=2.16 structure. Also, one confirmed and three candidate Lyα emitters at z=2.16 have $I - K \gtrsim 3.5$.

8. Attachments (Figures)

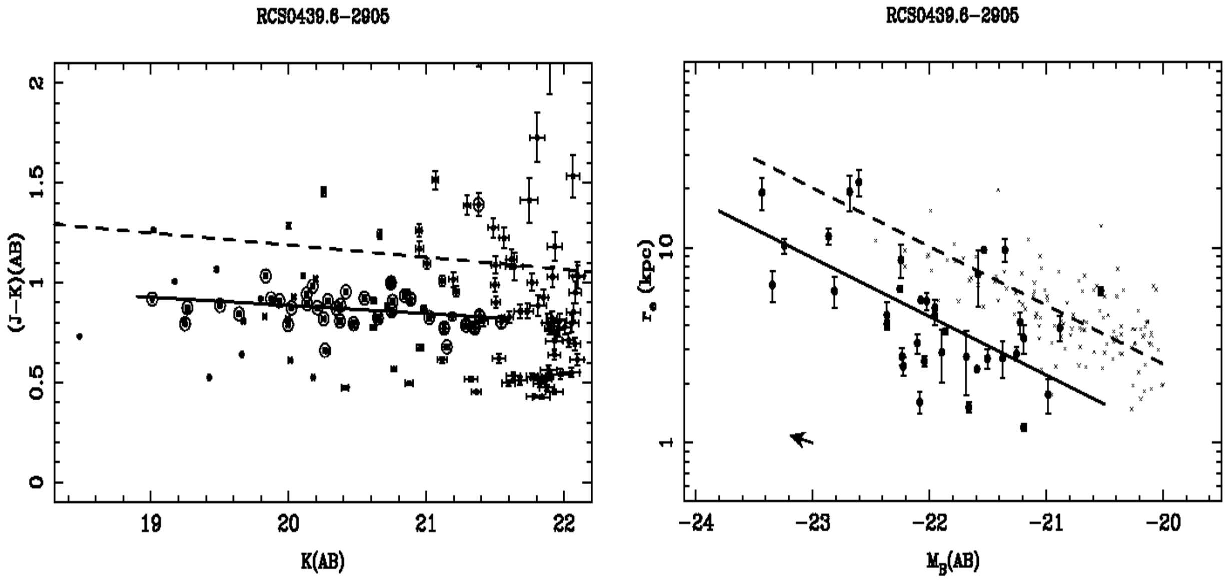

Fig. 2: Color-magnitude diagram (left) and Kormendy relation size-magnitude diagram (right) for the rich cluster RCS0439.6−2905 at z=0.97 (Barrientos et al. 2002), demonstrating the feasibility of using good-seeing ISAAC data to study galaxy morphologies at high redshift.

Left: points and error bars are plotted for all objects in the ISAAC field. Circled points show morphologically selected bulge-dominated galaxies. These galaxies define a red sequence similar to that observed in local clusters, but with approximately twice the scatter. The red sequence relation (solid line) is also bluer and slightly shallower than the relation observed for Coma (dashed line), redshifted to z=0.97.

Morphological classification was possible to K_{AB}=21.6 in this z=0.97 cluster, covering 2.6 magnitudes of the red sequence. using a 1.5 hour ISAAC exposure. Our proposed exposures on a z=2.16 protocluster will reach 0.6 magnitudes deeper, but the distance modulus between z=0.97 and z=2.16 is $2\overset{m}{.}0$, so we will probe only 1.2 magnitudes of the red sequence, equivalent to K_{AB}=20.2 on Figure 2a. This is obviously sufficient to determine the color and scatter of the red sequence, but not its slope.

Right: size-magnitude diagram for bulge-dominated galaxies in the field of RCS0439.6−2905. For comparison E/S0 galaxies in local clusters are shown as crosses, and the best-fit relation to them as a dashed line. The solid line shows a relation of the same slope fit to the bulge-dominated galaxies in the field of RCS0439.6−2905. The offset amounts to 1.2±0.1 magnitudes of luminosity evolution in B between z=0 and z=0.97. The scatter in the relation also appears higher at z=0.97. (The arrow shows the effect of changing the cosmology from Ω_M=0.2, Ω_Λ=0 to Ω_M=0.3, Ω_Λ=0.7.)

9. Justification of requested observing time and lunar phase

Lunar Phase Justification: For the FORS2 z'-band imaging, grey time is acceptable since even in grey time the background in the z' band is dominated by night sky lines. For the ISAAC imaging, bright time is fine.

Time Justification: We have 1.5 hrs of 0.5″ seeing ISAAC data in hand for a z=0.97 cluster, in which robust morphological classification is possible to K=19.7, covering $2\overset{m}{.}6$ of the red sequence (Fig. 2a). In a Λ=0.7 flat universe, the angular diameter distance does not change significantly from z=1 to z=2.16. Thus <0.6″ seeing will enable selection of bulge-dominated galaxies in our target cluster at z=2.16, as long as we image deep enough. If we integrate three times as long as at z=0.97, we will probe $0\overset{m}{.}6$ deeper, and since the distance modulus between z=0.97 and z=2.16 is $\sim2\overset{m}{.}0$ we will cover the brightest $1\overset{m}{.}2$ of the red sequence (neglecting luminosity evolution). There are 12 such galaxies with K_{AB}<22.4 and $I-K$>5 in our ISAAC fields; these are very likely to be morphological early-type galaxies, along with possibly some galaxies bluer in $I-K$. This should be sufficient to establish the color and scatter of the morphologically selected red sequence. Imaging redward of the 4000 Å break is required for accurate morphologies; we will achieve the required 4.5 hours' exposure in each ISAAC field by coadding H and K_s data. We want to detect K=22 galaxies with $J-K$=2 and $H-K$=1 at 5σ. Assuming 0.6″ seeing (0.7″ in J) and using an aperture with diameter 3 times the seeing, we require 2 hrs in J, 2.5 hrs in H, and 2 hrs in K_s. We have two existing ISAAC pointings near 1138−262, one with 2 hours K_s + 0.75 hours H + 1 hour J, and the other with 1.3 hours K_s, all with seeing 0.45″–0.7″. Therefore in this proposal we request exposure times of 0.7 hours K_s + 4.25 hours H + 3 hours J, for a total of 8 hours' exposure. Including overhead, this requires allocations of 1 hour for K_s and 6 hours for H, all in <0.6″ seeing, and 4 hours for J, for which we can accept 0.8″ seeing. In addition, we require a 1 hour allocation for a 2x2 binned FORS2 z'-band image reaching 5σ z_{AB} = 25.6. For this image 1″ seeing is acceptable, given the greater sensitivity and larger pixel scale of FORS2 and that we do not need to measure morphologies in z'.

Calibration Request: Standard Calibration

10. Report on the last use of ESO facilities

67.A-0544 / P. Hall / Spectroscopy of Candidate Reddened Quasars from SDSS+2MASS

Telescope	Instrument	Obs. Dates	Completion (%)	Time lost (%)	Reason
NTT	EMMI	17-20 Apr 2001	100%	5%	technical

Current status of obtained data: paper-submitted

Remarks: No reddened quasars found, indicating that SDSS is very complete even for very reddened quasars (paper in preparation). Several candidates were carbon stars, to appear in Margon et al. (submitted). One highly reddened FIRST/2MASS quasar was found as well (Hall et al. in preparation). Observations of SDSS gravitational lens candidates also made to take advantage of excellent seeing; no lenses found, but one quasar binary and one quasar companion galaxy found (paper in preparation). Observations also made of the strange [OII]-without-[OIII] galaxy RCS 1443+0805 (paper in preparation).

11. Applicant's publications related to the subject of this application during the past two years

Hall et al., 2001, AJ, 121, 1840: Galaxies in the Fields of $z\sim1.5$ Radio-Loud Quasars

Kurk, Roettgering, Pentericci, Miley et al. 2000, A&A, 358, L1: A Search for Clusters at High Redshift I. Candidate Lyα emitters near 1138−262 at z = 2.2

Pentericci, Kurk, Roettgering, Miley et al. 2000, A&A, 361, L25: A Search for Clusters at High Redshift II. A proto cluster around a radio galaxy at z = 2.16

Pentericci, McCarthy, Roettgering, Miley et al. 2001, ApJS, 135, 63: NICMOS Observations of High-Redshift Radio Galaxies: Witnessing the Formation of Bright Elliptical Galaxies?

Pentericci, van Reeven, Carilli, Roettgering & Miley 2000, A&AS, 145, 121: VLA radio continuum observations of a new sample of high redshift radio galaxies

Venemans, Kurk, Miley, Roettgering, van Breugel, Carilli, De Breuck, Ford, Heckman, McCarthy & Pentericci, 2002, ApJ, 569, L11: The Most Distant Structure of Galaxies Known: A Protocluster at z = 4.1

Carilli, Harris, Pentericci, Roettgering, Miley, Kurk & van Bruegel 2002, ApJ, 567, 781: The X-Ray-Radio Alignment in the z=2.2 Radio Galaxy PKS 1138−262

Pentericci, Kurk, Roettgering, Miley & Venemans 2002, to appear in "Tracing cosmic evolution with galaxy clusters": The population of galaxies in the forming cluster around the radio galaxy MRC 1138-262 at z=2.2

Kurk, Venemans, Roettgering, Miley & Pentericci 2002, to appear in "Tracing cosmic evolution with galaxy clusters": A search for high redshift clusters associated with radio galaxies at $2 < z < 4$

12. List of targets proposed in this programme

Run	Target/Field	α	δ	Eq.	Mag.	Diam.	Additional info	Reference star
A	PKS 1138−262	11:40:48.36	-26:29:10.6	J2000	K_s=16.1			
B	PKS 1138−262	11:40:48.36	-26:29:10.6	J2000	K_s=16.1			
C	PKS 1138−262	11:40:48.36	-26:29:10.6	J2000	K_s=16.1			

13. Scheduling requirements

14. Instrument configuration

Telescope	Instrument	Parameter	Value or list
UT1	ISAAC	SWI	J,J_s,H,K_s
UT4	FORS2	IMG	z(GUNN)#78